Coherent Pion Production at MINERvA

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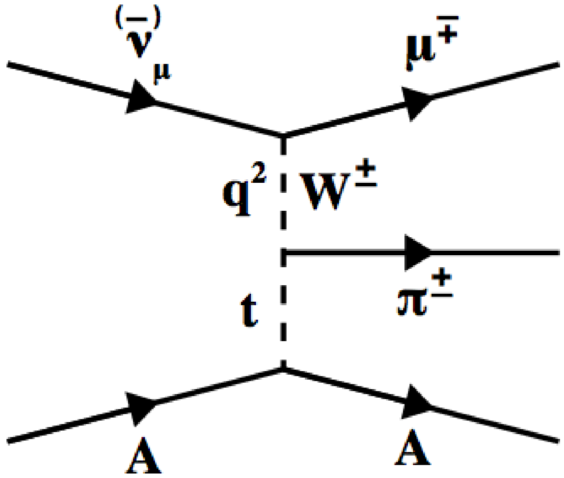
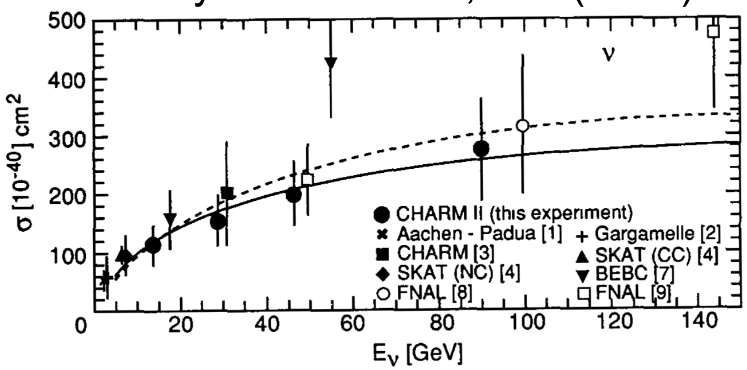
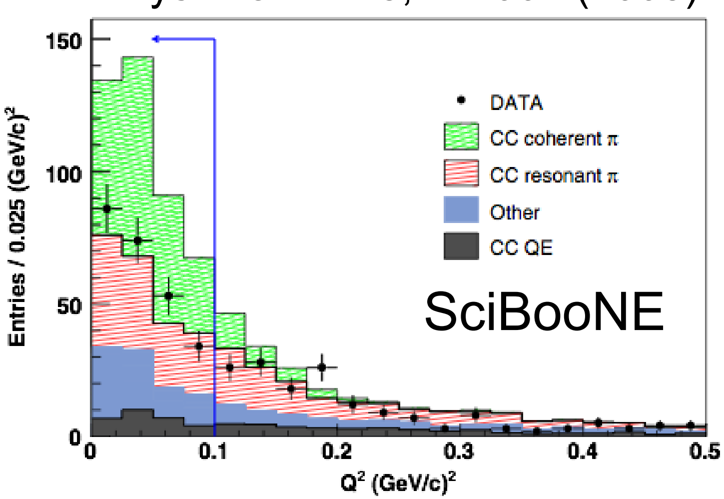


Phys. Lett. B 313, 267 (1993)



Phys. Rev. D 78, 112004 (2008)



Coherent Pion Production

- Produces forward lepton and pion while leaving nucleus in its ground state
- Model independent features:
  - No nuclear break-up
  - Small 4-momentum transfer to the nucleus, $|t|=|(p_\nu-p_\mu-p_\pi)|^2$
- Background to oscillation experiments
- Model used by oscillation experiments (Rein-Sehgal) agrees with higher energy data
- Recent experiments (K2K,SciBooNE) found no evidence for this process at low energy (E_ν~1 GeV)

T2K & Coherent Pion Production

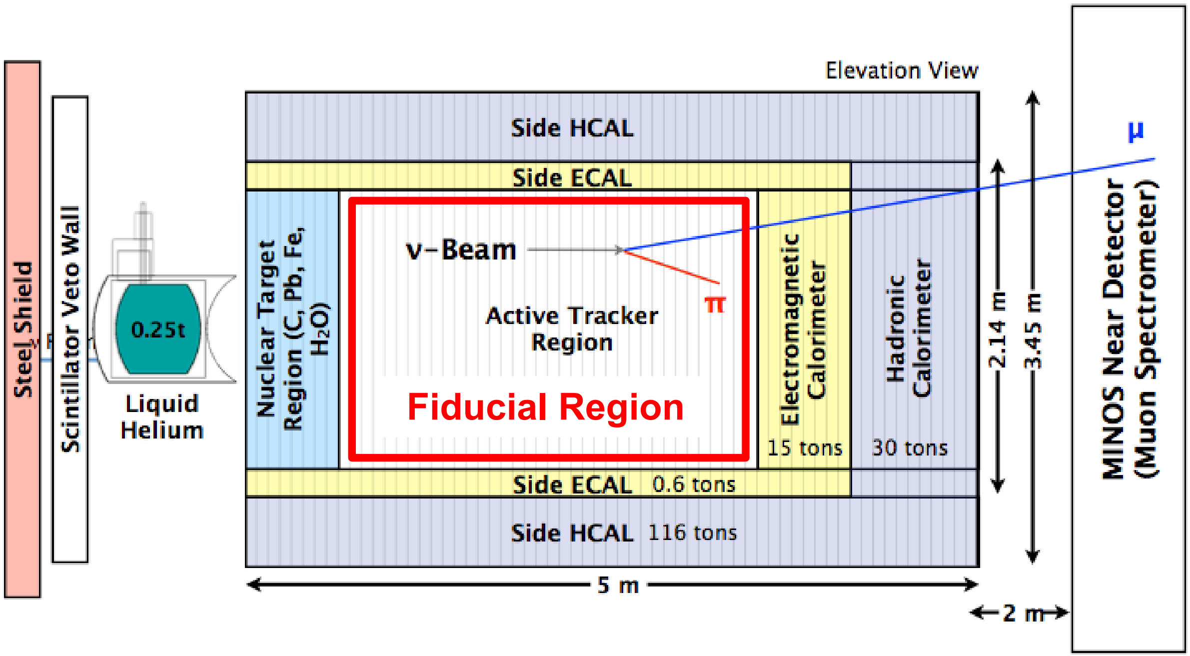
arXiv:1502.01550

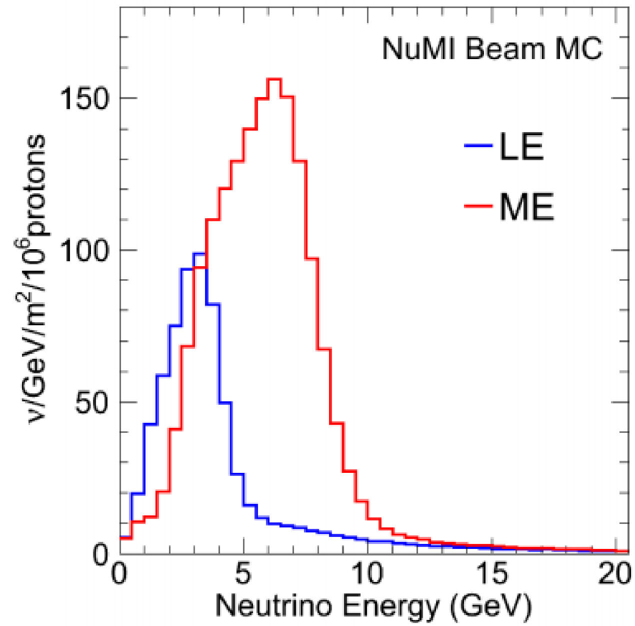
Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

T2K relative uncertainty (1σ) on the predicted ν_μ CC and ν_e CC oscillated event rate

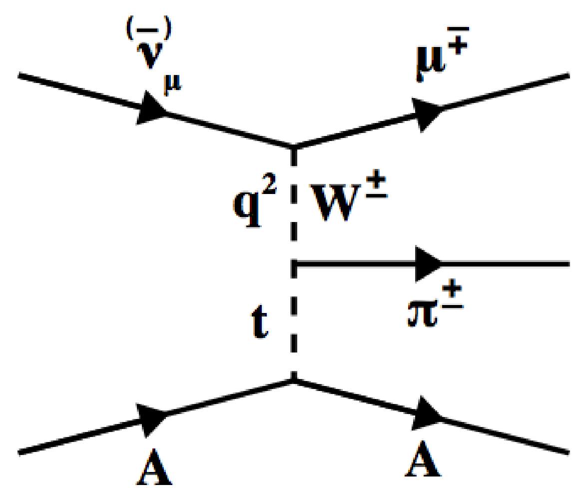
- Due to non-observation at low energy (E_ν~1 GeV) by recent experiments, T2K has applied a 100% uncertainty on the coherent pion production rate
- Neutrino-nucleus interaction model uncertainties are T2K's largest source of systematic error for their oscillation analyses
- The uncertainty on the coherent pion production rate is a significant contribution to these uncertainties

Coherent Pion Production at MINERvA

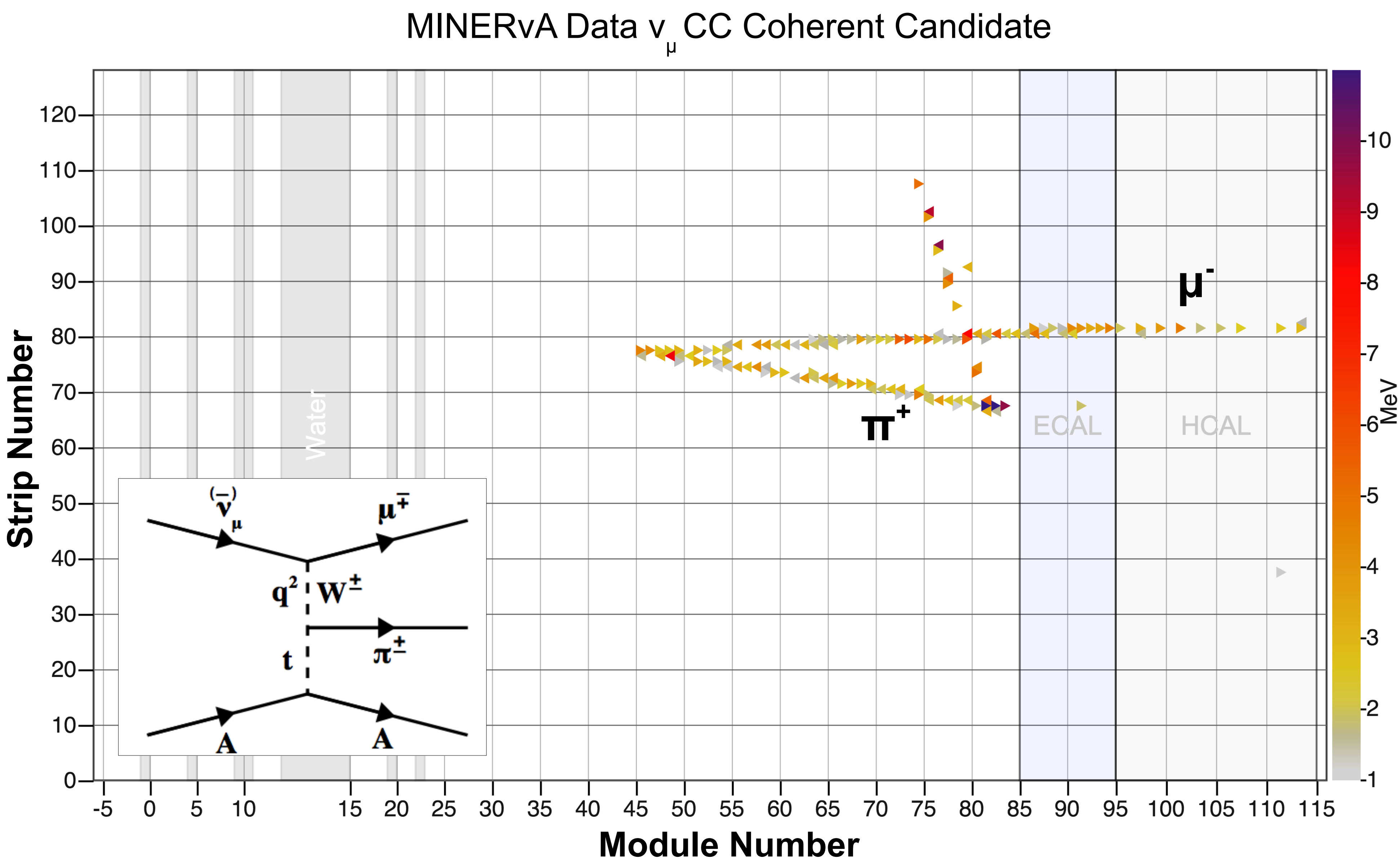




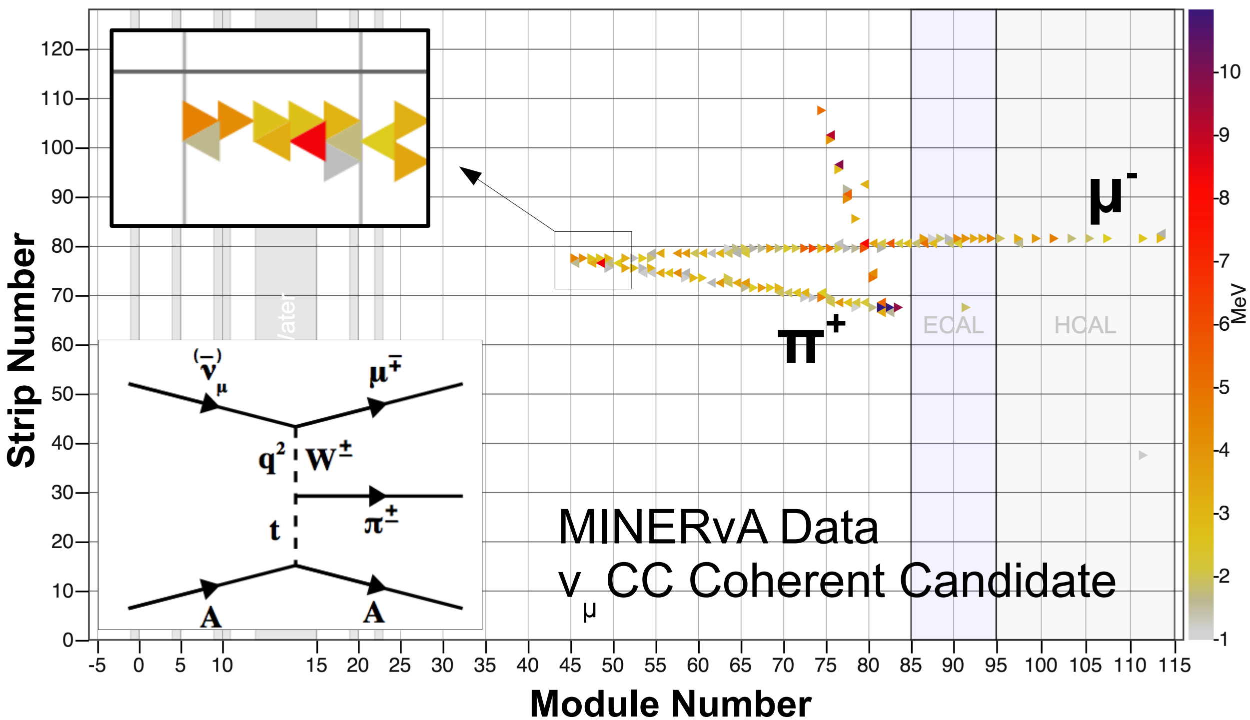
- MINERvA has measured coherent pion production on carbon in its fully active tracker region for $1.5 < E_\nu < 20$ GeV
- Model-independent identification of coherent interactions by
  - resolving vertex activity
  - reconstructing $|t|=|(p_\nu-p_\mu-p_\pi)|^2$

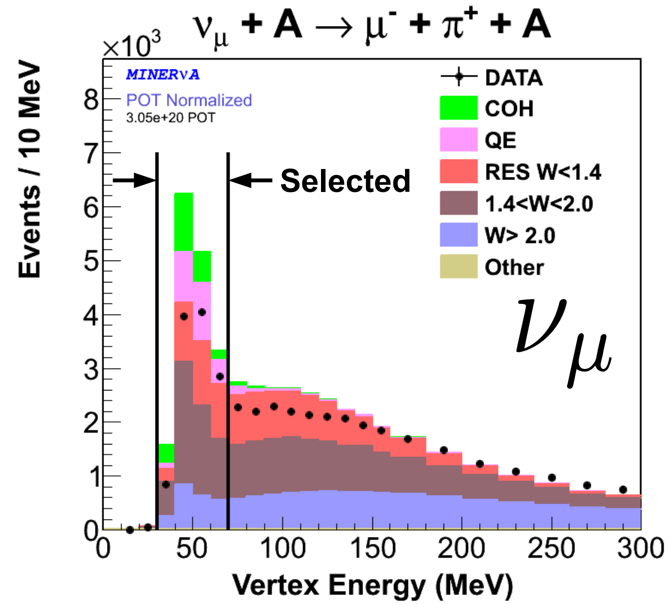


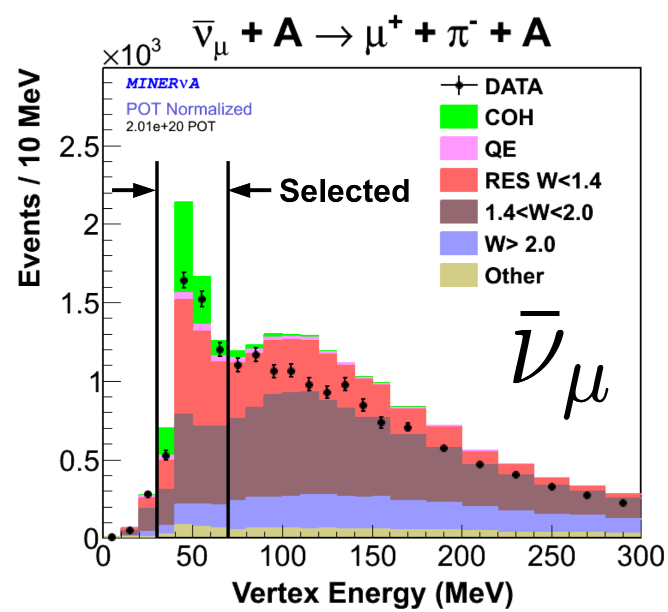
Coherent Pion Production at MINERvA



Event Selection: Vertex Energy

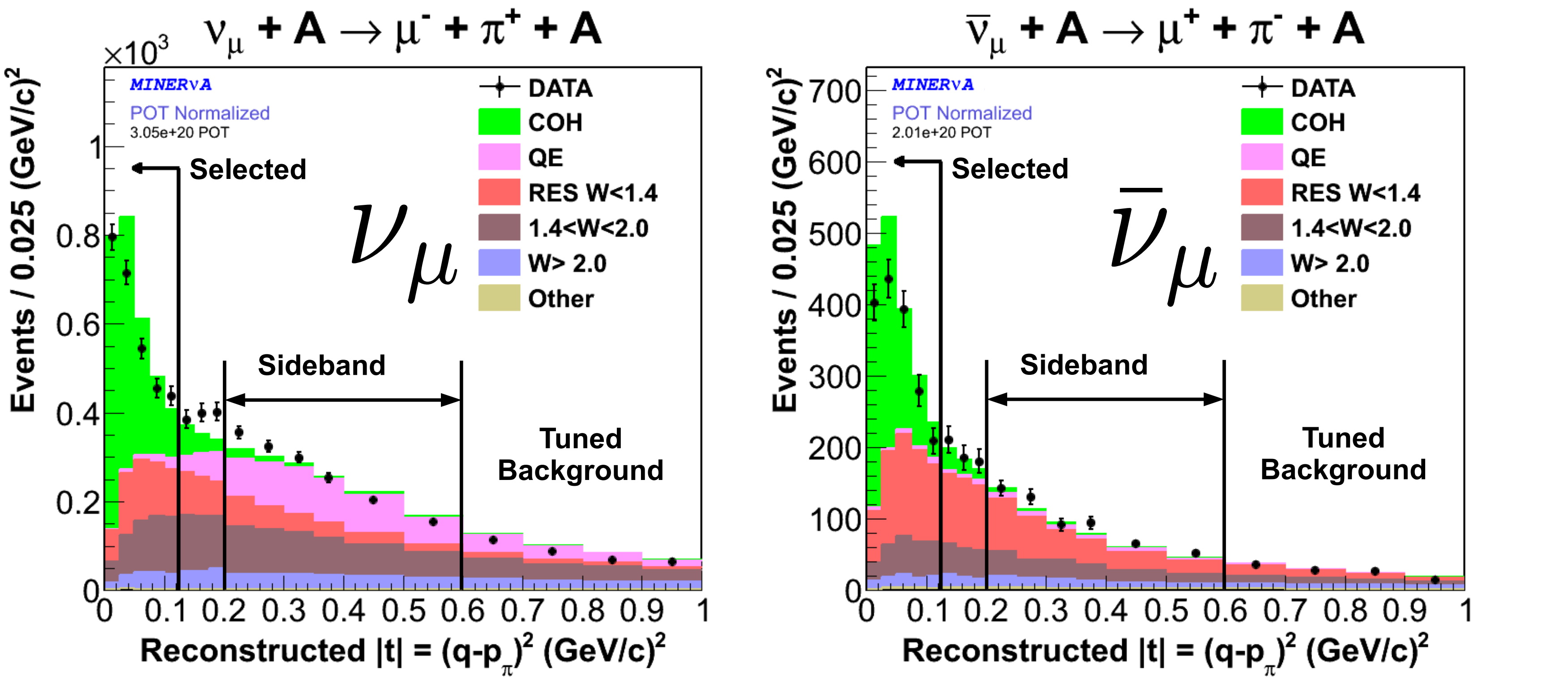


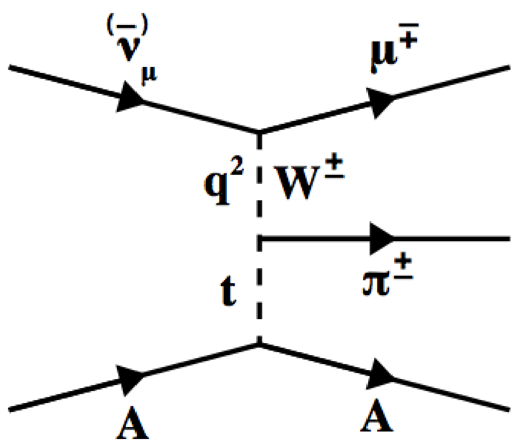




Visible energy within a region around the vertex is required to be consistent with a minimum ionizing muon and pion: $30 < E_{vtx} < 70$ MeV

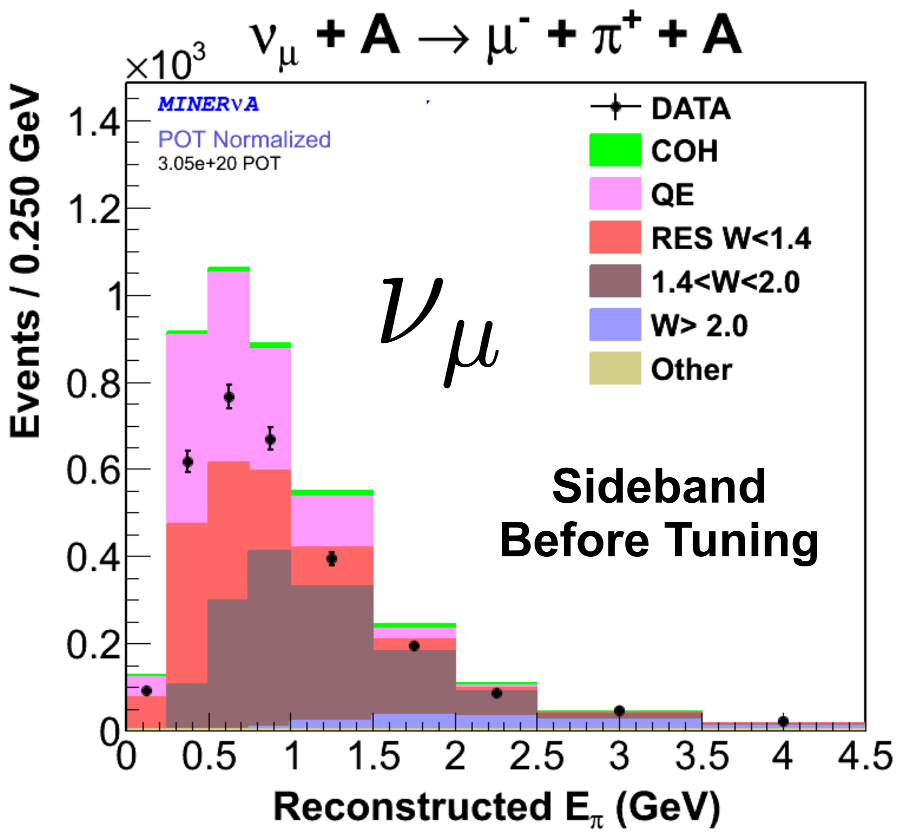
Event Selection: |t|

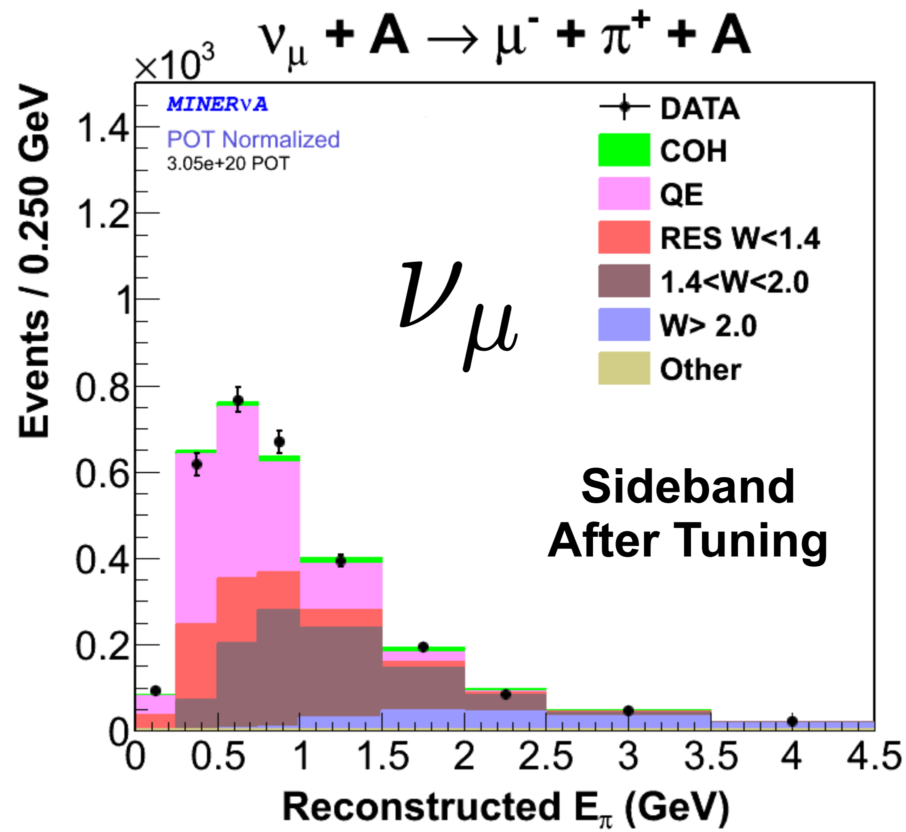




- MINERvA is able to reconstruct the 4-momentum transfer to the nucleus, $|t|=|(p_\nu-p_\mu-p_\pi)|^2$
- Coherent candidates: $|t| < 0.125$ GeV^2
- Sideband for tuning background: $0.2 < |t| < 0.6$ GeV^2

Background Tuning

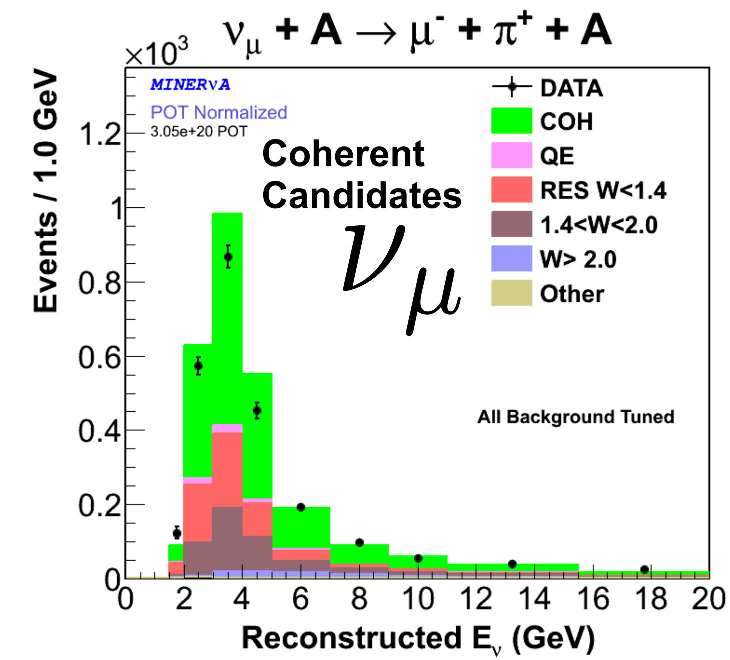


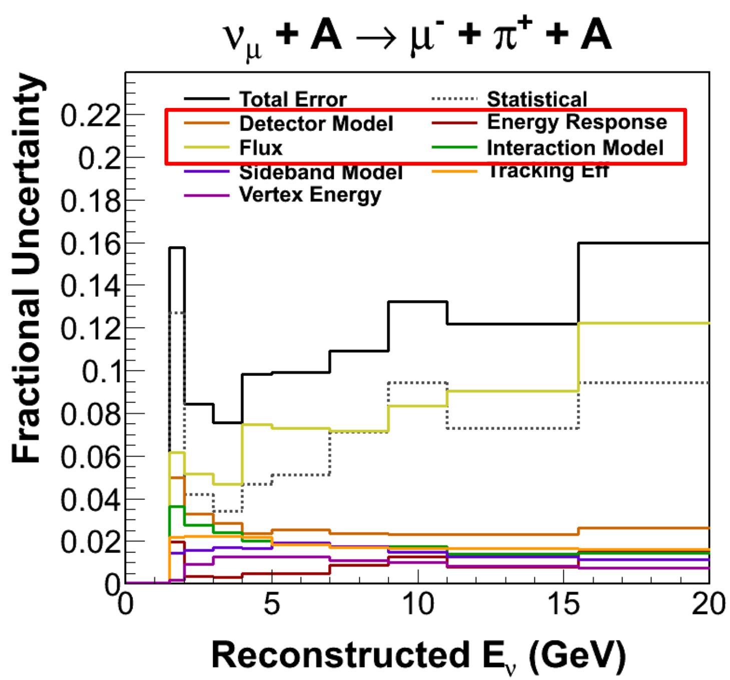


- Signal & background simulated by GENIE neutrino event generator
- Background normalizations are fit in E_π in the sideband: $0.2 < |t| < 0.6$ GeV^2

Background	ν_μ	Anti-ν_μ
CCQE	0.7 +/-0.3	1.0 (fixed)
Non-CCQE W < 1.4 GeV	0.6 +/-0.3	0.7 +/-0.1
1.4 < W < 2.0 GeV	0.7 +/-0.1	0.6 +/-0.1
W > 2.0 GeV	1.1 +/-0.9	1.9 +/-0.3

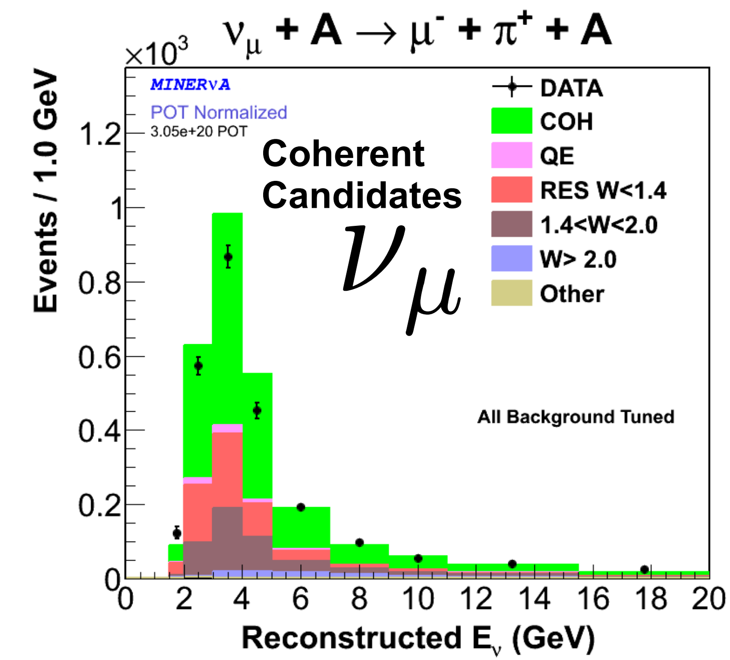
Systematics (1)

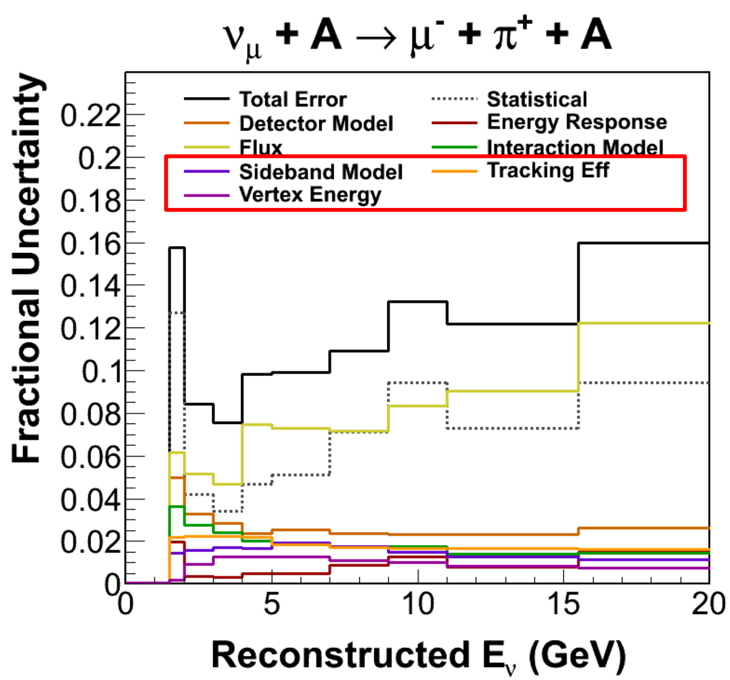




- Flux Prediction
  - Hadron production constrained by external data (NA49)
  - Beam focusing & unconstrained interactions
- Neutrino-Nucleus Interaction Model
  - $M_{A,RES}$, intra-nuclear scattering, etc.
- Detector Model
  - GEANT hadron propagation
  - Detector alignment wrt neutrino beam
- Energy Response
  - Muon energy uncertainty from range/curvature
  - Pion/proton response constrained by test beam program

Systematics (2)





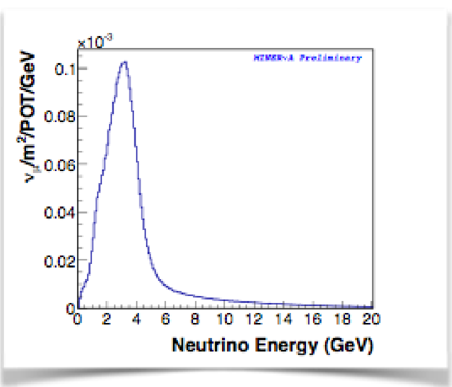
- Sideband Model
  - Accounts for remaining θ_π disagreement in the sideband after background tuning
- Tracking Efficiency
  - Accounts for data-MC differences in muon reconstruction efficiency due to unsimulated pile-up in MINOS
- Vertex Energy
  - Accounts for unsimulated multi-nucleon effects
  - Guided by MINERvA's CCQE results, add a final state proton to 25% of events with a target neutron

Cross Section Calculation

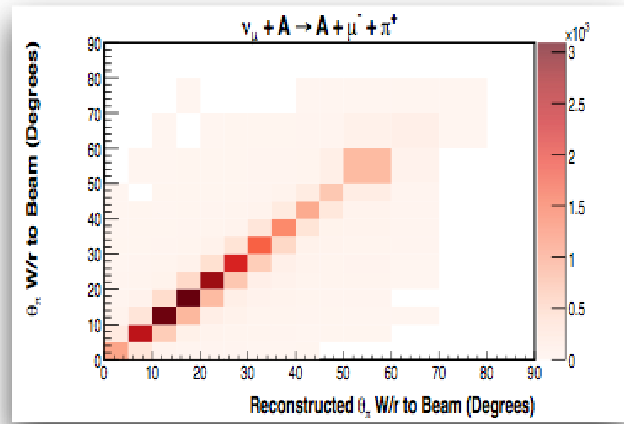
$$\left(\frac{d\sigma}{d\theta_\pi}\right)_i = \frac{1}{T_n \Phi_\nu} \cdot \frac{1}{(\Delta\theta_\pi)_i} \cdot \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkgd})}{\epsilon_i}$$

Number of scattering targets

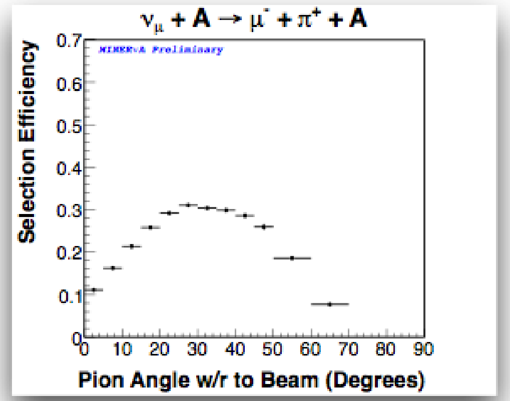
Flux prediction



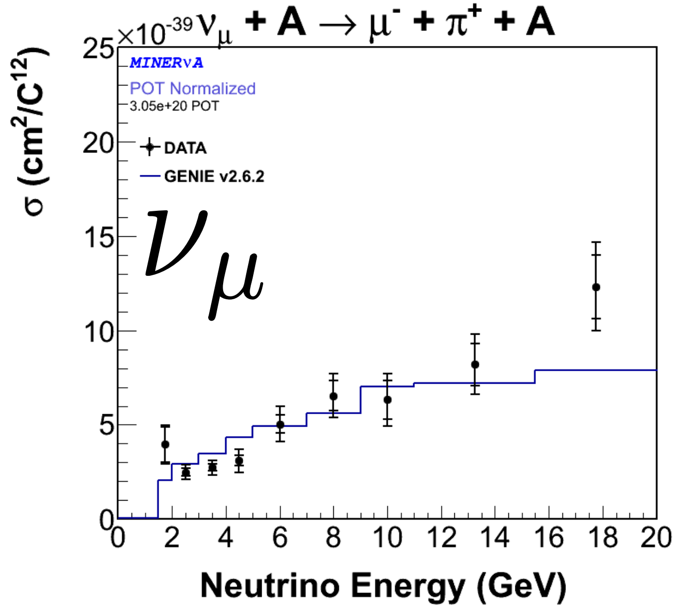
Unfolding to correct for resolution

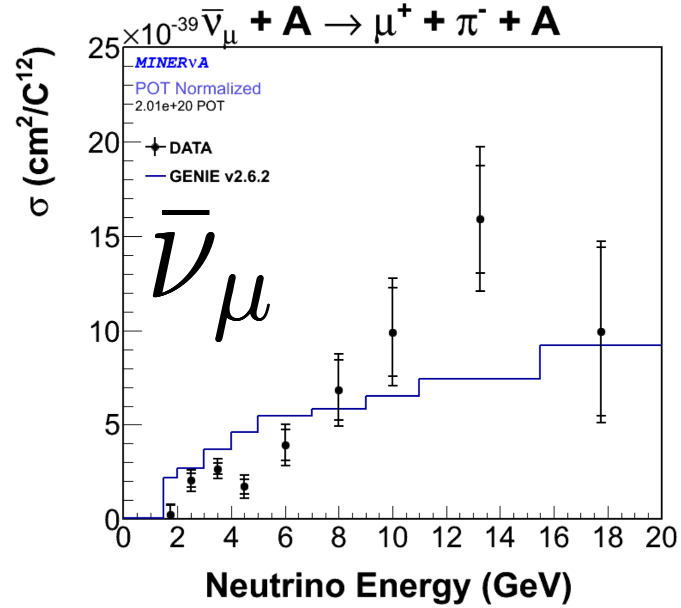


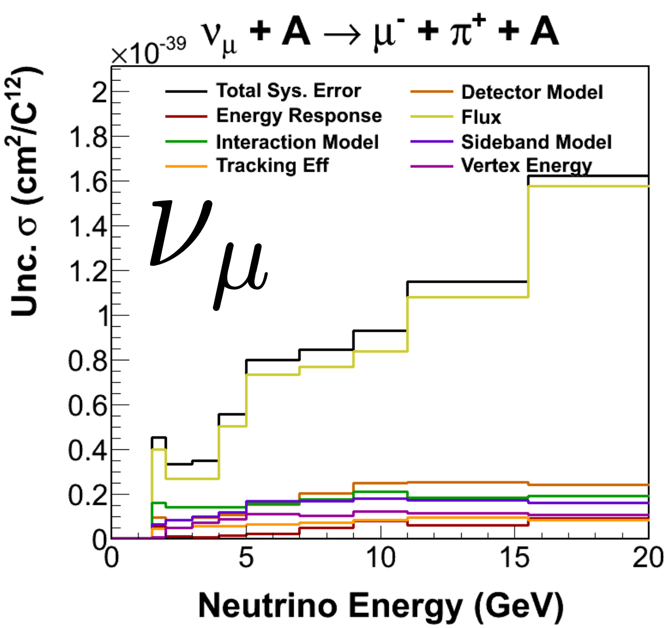
Efficiency & acceptance

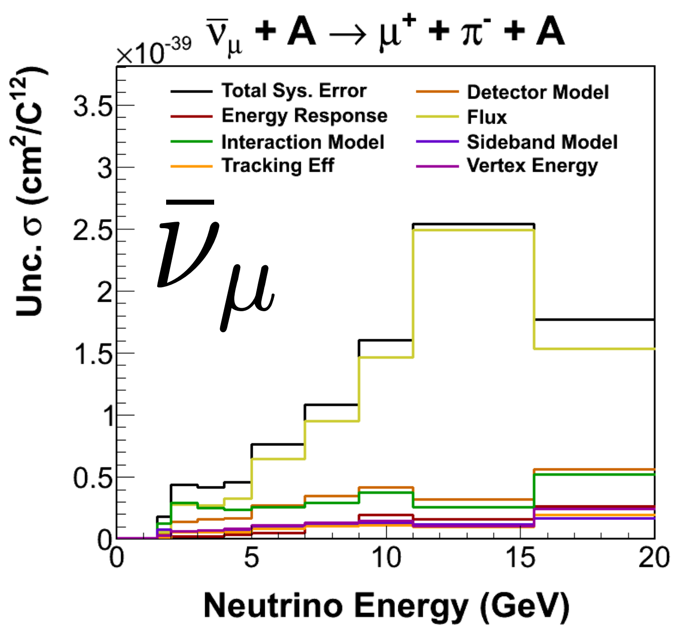


Cross Section Results (1)





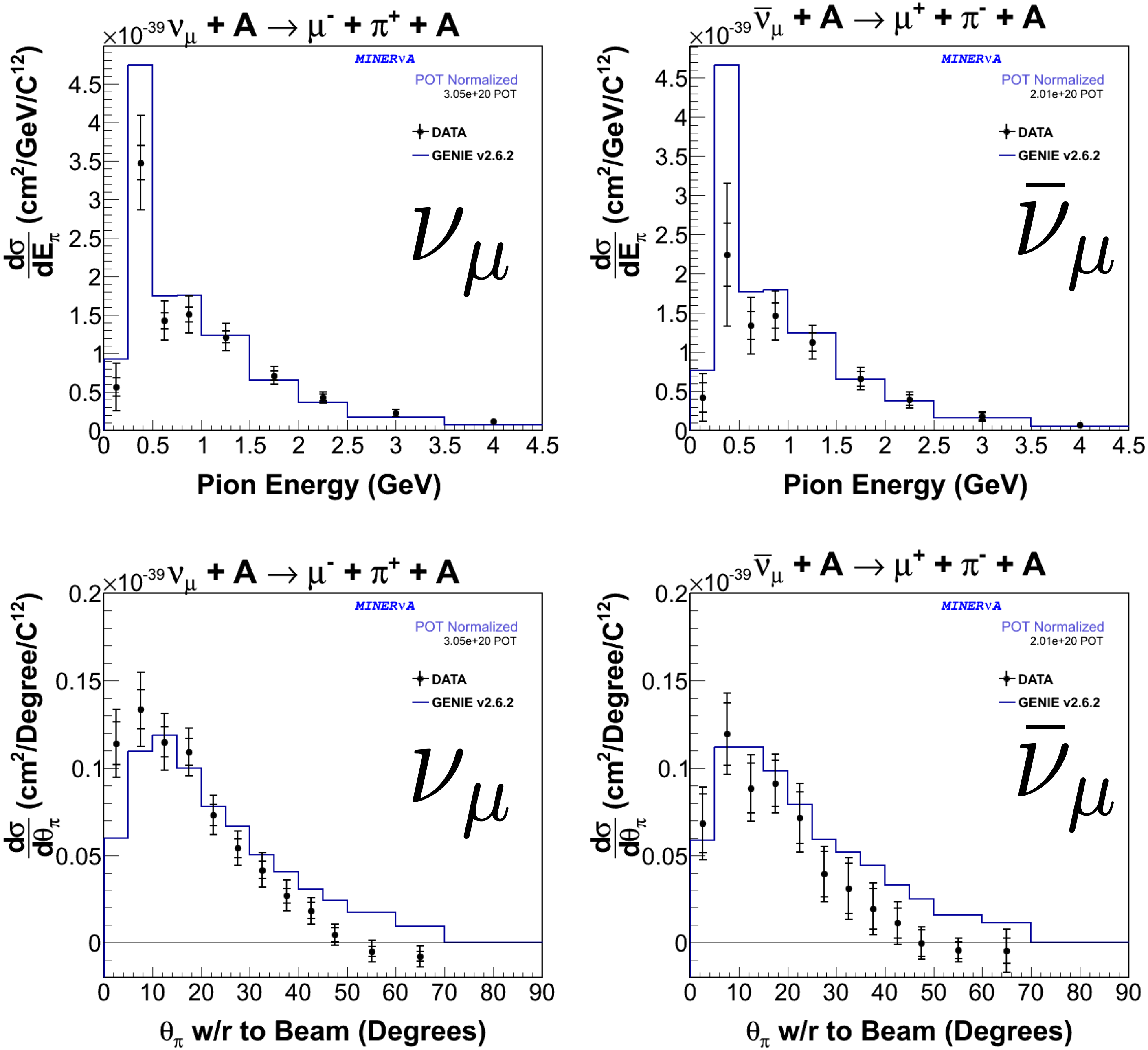




At few GeV, the cross section from MINERvA data is smaller than the prediction of the Rein-Sehgal coherent model as implemented in GENIE

Phys. Rev.Lett. 113, 261802 (2014)

Cross Section Results (2)



MINERvA data for coherent scattering exhibits harder and more forward pions than the prediction of the Rein-Sehgal coherent model as implemented in GENIE

Phys. Rev.Lett. 113, 261802 (2014)

Future Results: Measuring dσ/dQ^2

- Oscillation experiments use the Rein-Sehgal model for coherent scattering:
  - Based on Adler's PCAC theorem which relates the coherent scattering cross section at Q^2=0 to the pion-nucleus elastic scattering cross section:

$$\left.\frac{d\sigma}{dx\,dy\,d|t|}\right|_{Q^2=0} = \frac{G^2 M E_\nu}{\pi^2} f_\pi^2 (1-y) \left.\frac{d\sigma(\pi A \to \pi A)}{d|t|}\right|_{E_\pi = y E_\nu}$$

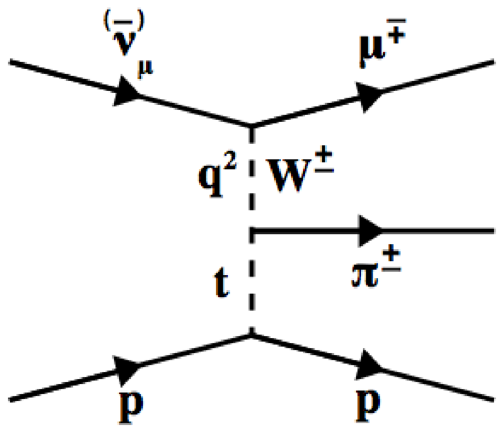
  - Extrapolates to Q^2 > 0 by modifying the above equation with a multiplicative dipole form factor:

$$F^2_{dipole}(Q^2) = 1/(1+Q^2/m_A^2)^2$$

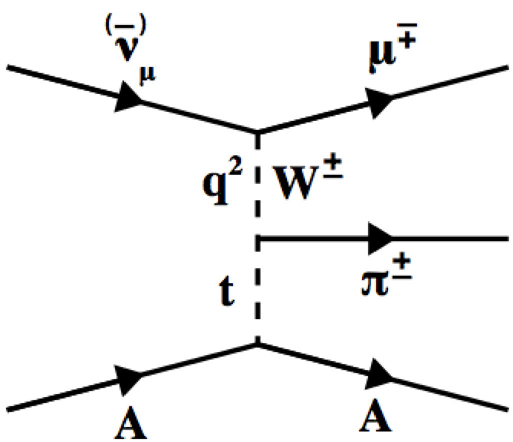
  - Assumes no vector current contribution, and therefore no vector – axial vector interference
- We can test these assumptions of the Rein-Sehgal model by measuring dσ/dQ^2 for both neutrinos and antineutrinos

Future Results: Diffractive Pion Production (1)

Diffractive

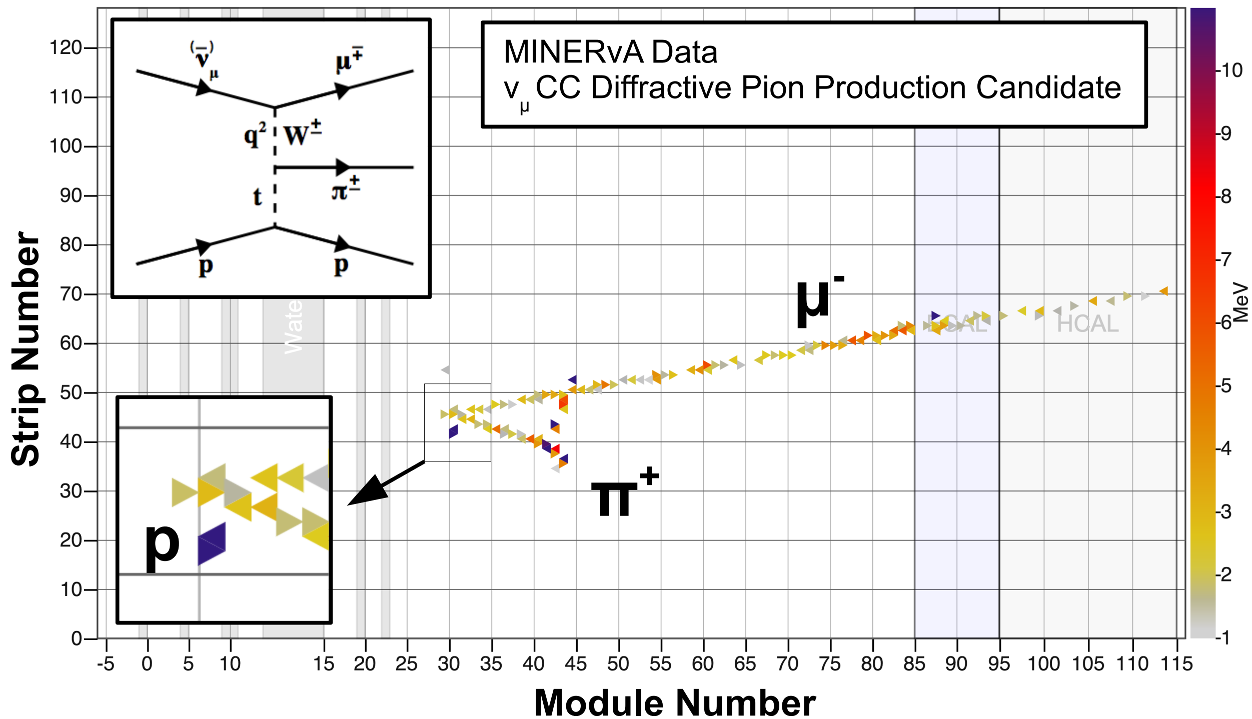


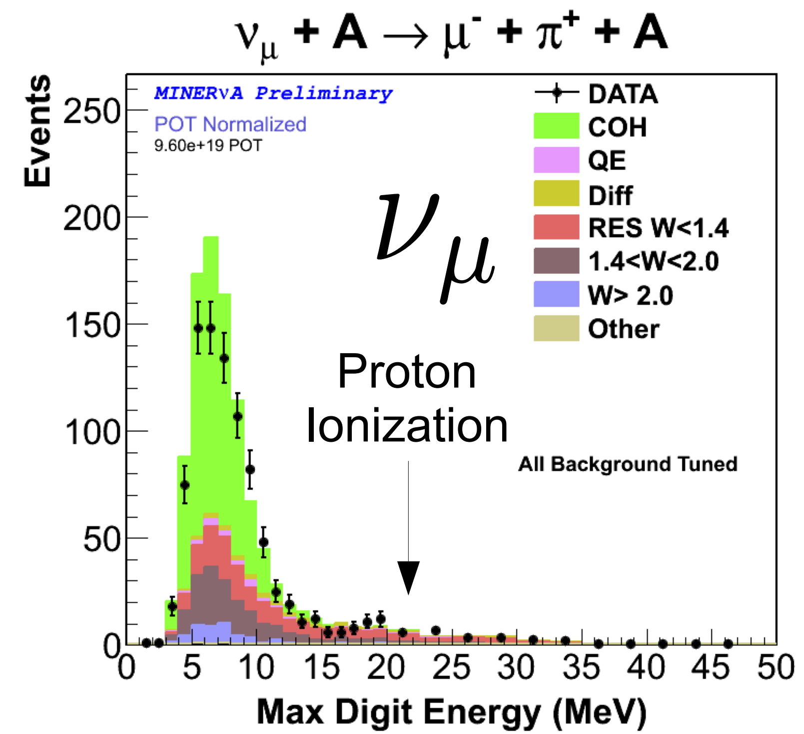
Coherent



- Diffractive pion production off free protons
  - Not simulated in GENIE
  - Indistinguishable from coherent pion production when the recoil proton is undetected
- MINERvA's scintillator (CH) has equal numbers of free protons and carbon nuclei
- Estimating the acceptance and using a calculation by B. Kopeliovich, we estimate the contribution from diffractive scattering would be equivalent to 7% (4%) of the ν_μ (anti-ν_μ) GENIE coherent cross section on carbon

Future Results: Diffractive Pion Production (2)





Search for diffractive pion production among the coherent candidates by looking for a large energy deposition in a single strip near the event vertex resulting from the recoil proton ionization

Summary

- Improved knowledge of coherent pion production is important to current and future oscillation experiments
- MINERvA has made a model-independent measurement of coherent pion production
- In comparison to the coherent pion production model (Rein-Sehgal) used in oscillation experiments, MINERvA data exhibits
  - a lower production rate at few-GeV E_ν
  - harder, more forward pions
- Future MINERvA results will include
  - $d\sigma/dQ^2$ measurement to further test the Rein-Sehgal coherent pion production model
  - a search for diffractive pion production off free protons

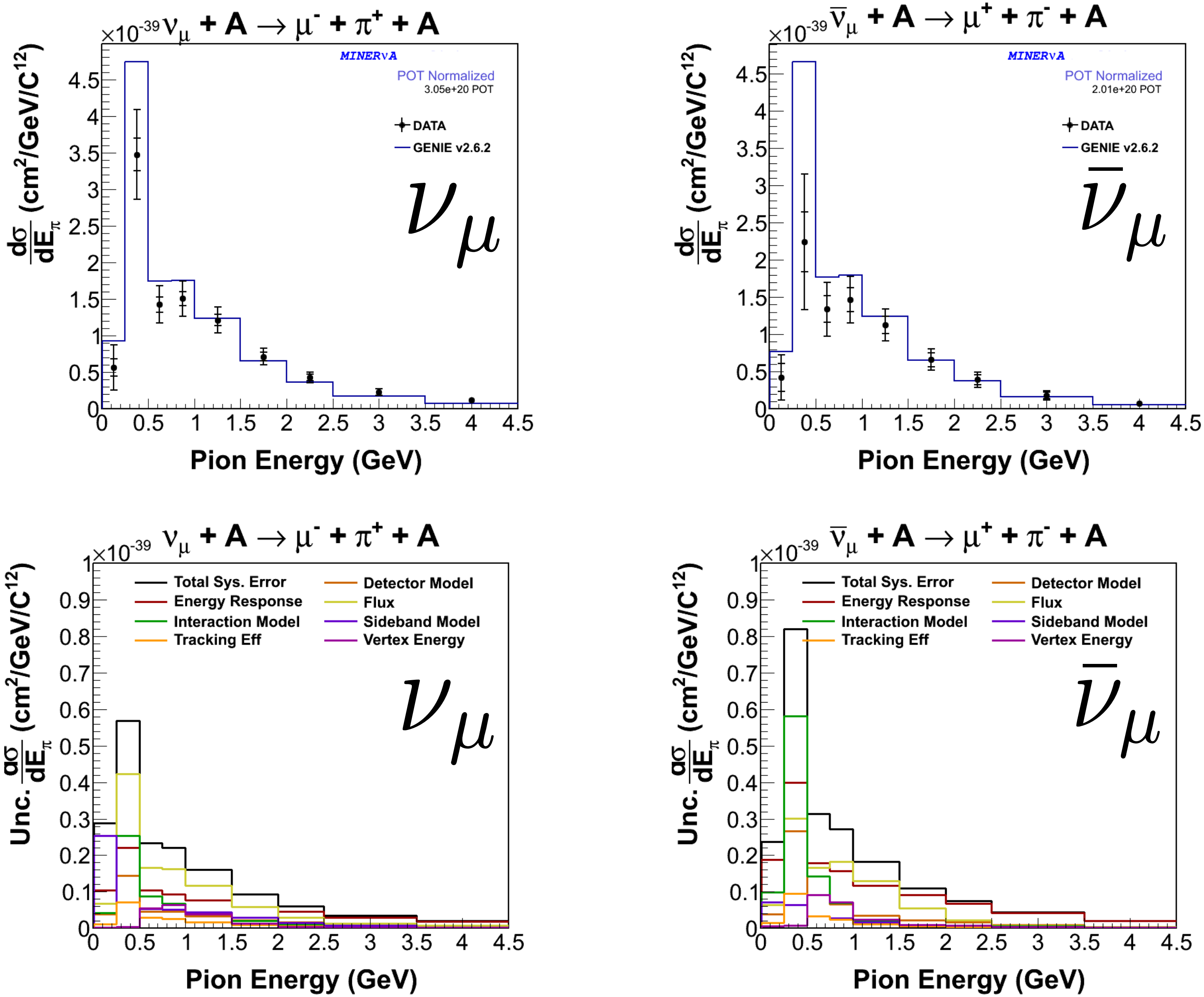
Thank You

The MINERvA Collaboration

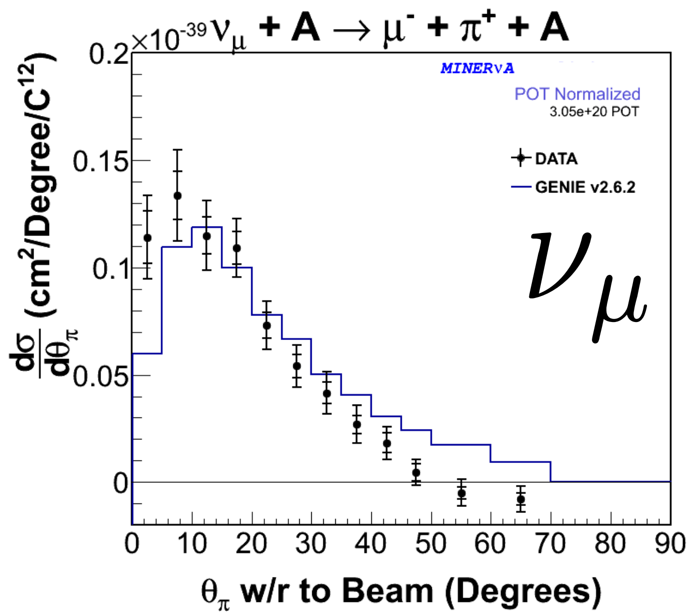
2014 Summer Meeting, Duluth, Minnesota

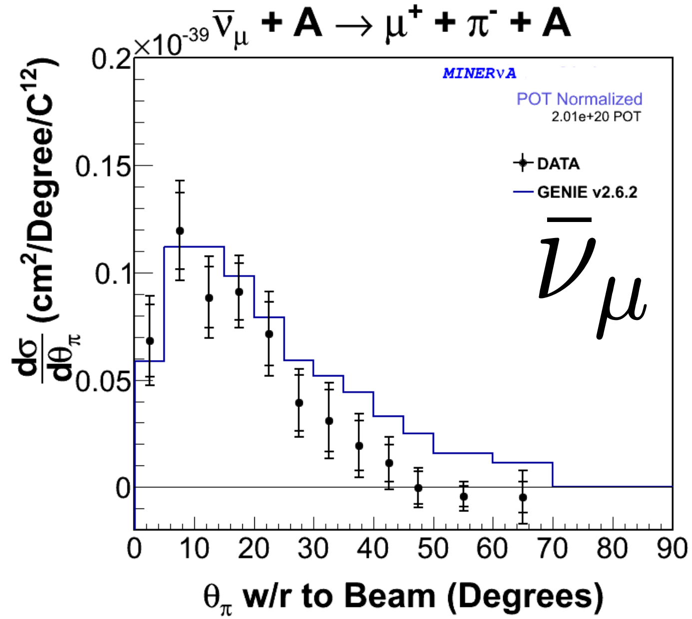
Backup

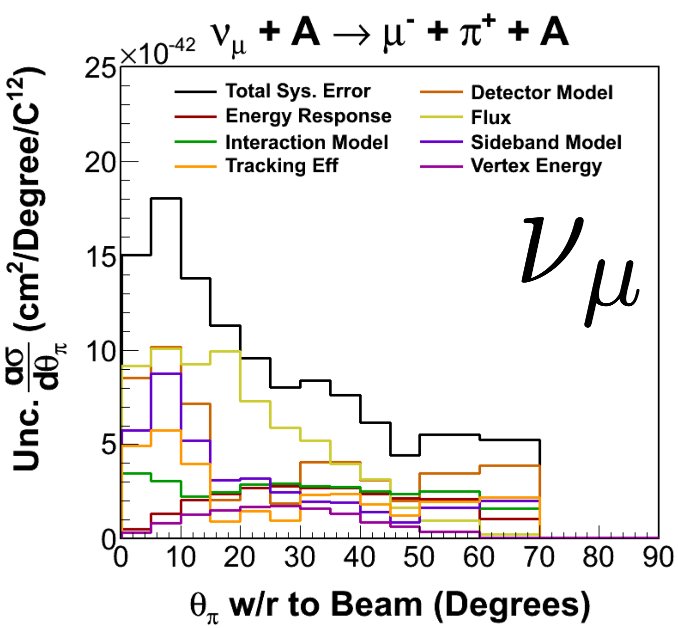
Cross Section Results: $d\sigma/dE_{\pi}$

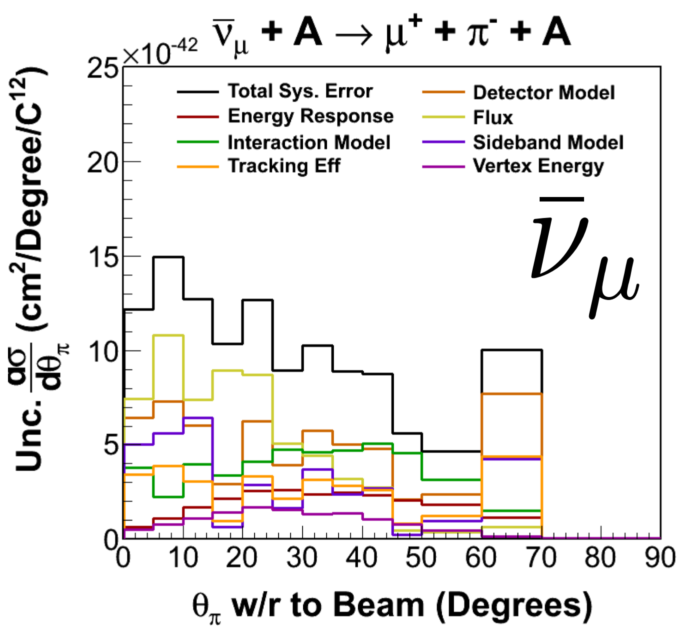


Cross Section Results: $d\sigma/d\theta_{\pi}$

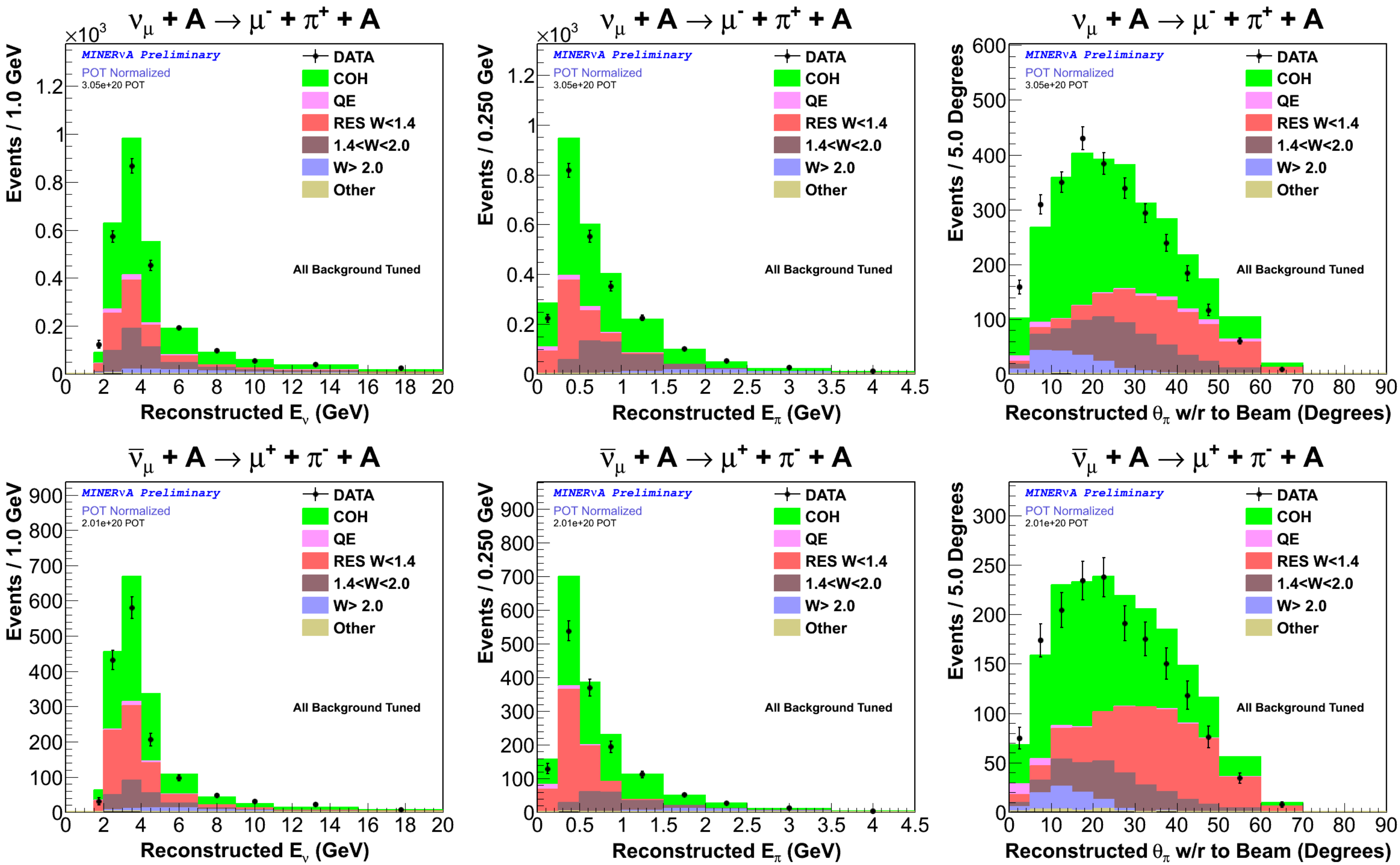




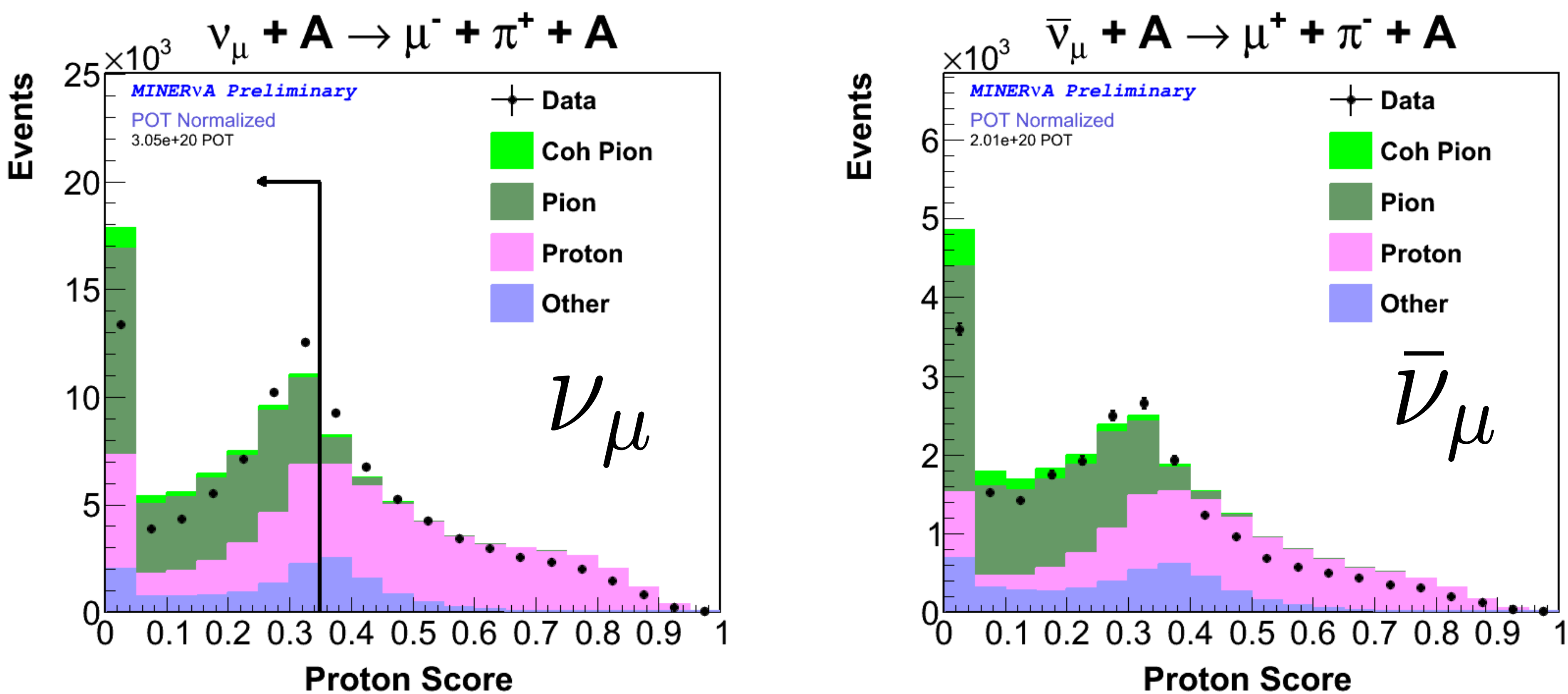




Selected Event Distributions

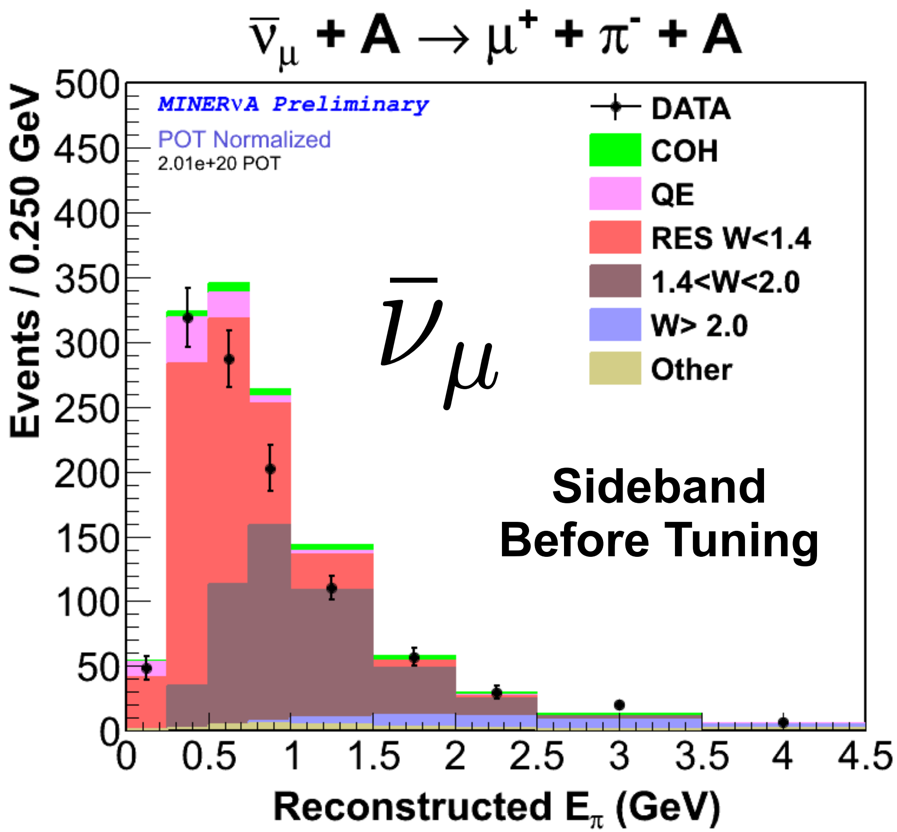


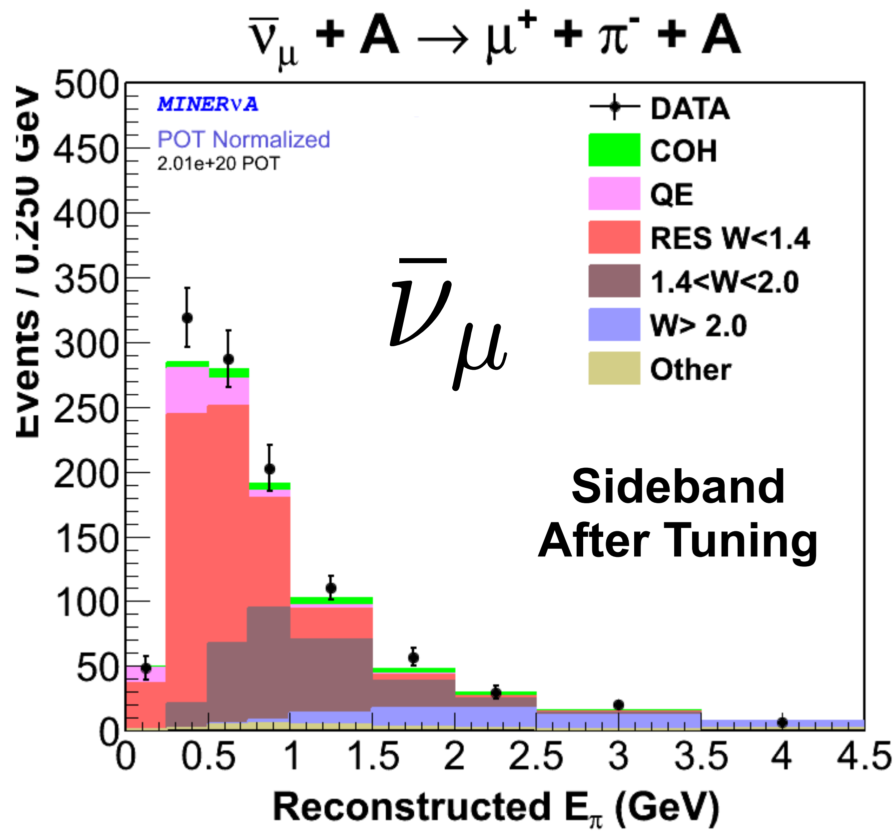
Event Selection: Proton Score



- Proton Score: dEdX proton likelihood of reconstructed hadron
- For neutrino sample, require proton score < 0.35 to reduce proton background, particularly CCQE

Background Tuning: Antineutrino

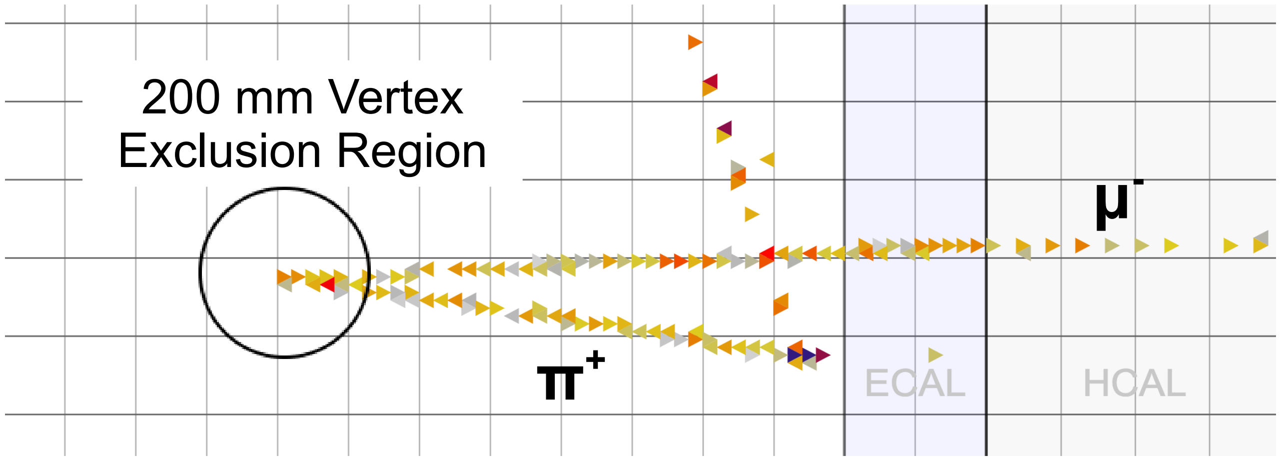




- Signal & background simulated by GENIE neutrino event generator
- Background normalizations are fit in E_π in the sideband: $0.2 < |t| < 0.6$ GeV^2

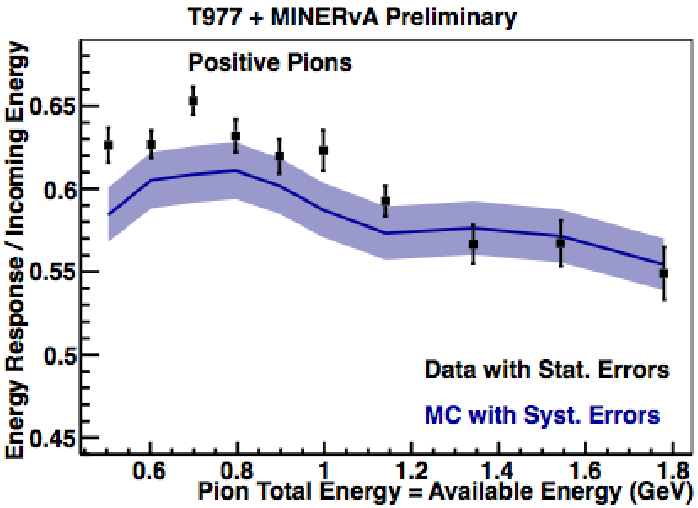
Background	ν_μ	Anti-ν_μ
CCQE	0.7 +/-0.3	1.0 (fixed)
Non-CCQE W < 1.4 GeV	0.6 +/-0.3	0.7 +/-0.1
1.4 < W < 2.0 GeV	0.7 +/-0.1	0.6 +/-0.1
W > 2.0 GeV	1.1 +/-0.9	1.9 +/-0.3

Kinematics Reconstruction

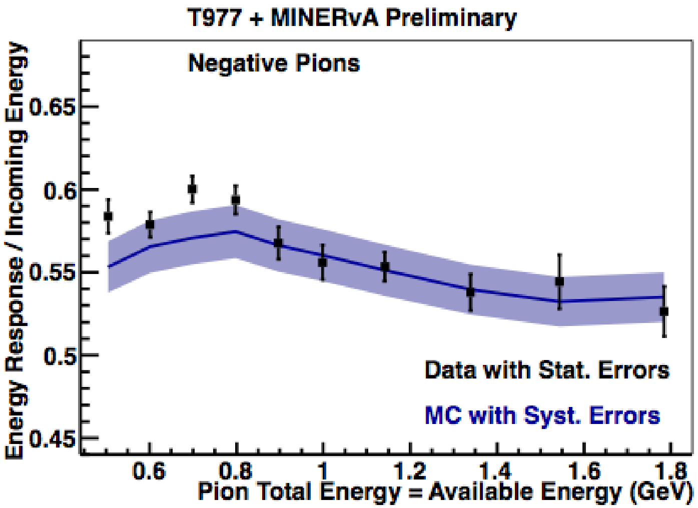


- We accurately measure p_μ for muons reconstructed in both MINERvA & MINOS
- Since most pions interact in MINERvA, E_π is reconstructed as the sum of:
  - total non-muon calorimetric energy > 200 mm from event vertex
  - Mean single pion calorimetric energy (60 MeV) within 200 mm from event vertex
- Vertex exclusion region minimizes sensitivity to mis-modeling vertex activity in background interactions
- $E_\nu = E_\mu + E_\pi$ (assumes zero energy transfer to nucleus)
- Assume neutrino direction is parallel to beam axis
- $|t| = |(q - p_\pi)^2| = |(p_\nu - p_\mu - p_\pi)^2|$

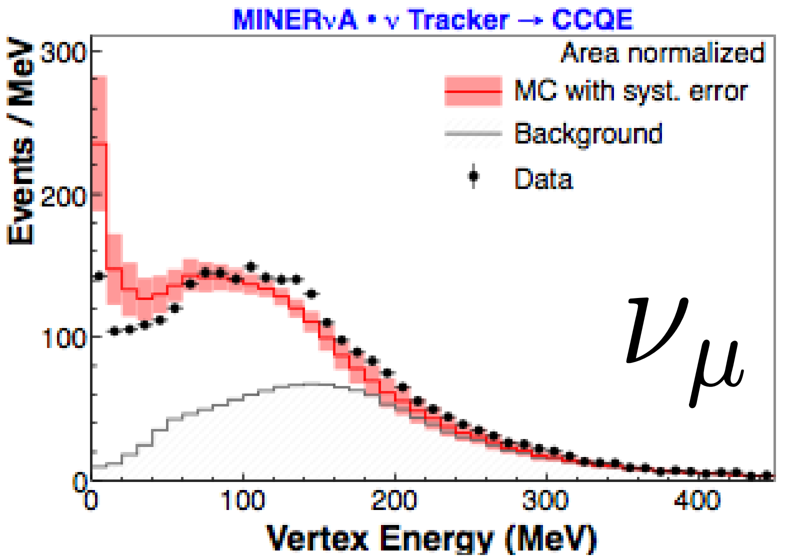
Systematics: Hadronic Response

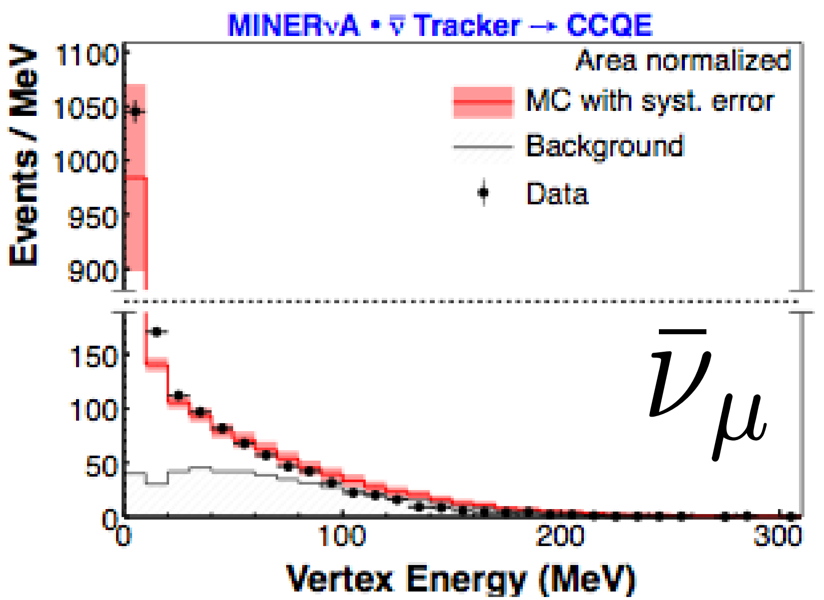


- MINERvA test beam program: scaled-down version of MINERvA detector in a tertiary pion beam at the Fermilab Test Beam Facility
- MINERvA's response to pions (protons) constrained to 5% (3%)



Systematics: Vertex Energy





MINERvA's CCQE results found an excess in vertex energy in data compared to the GENIE prediction
Phys. Rev. Lett. 111, 022501 (2013)
Phys. Rev. Lett. 111, 022502 (2013)

A fit to this excess prefers the addition of a final state proton with KE < 225 MeV to 25% of events with a target neutron

Motivated by these results, we estimated the effect of mis-modeling vertex activity on our analysis by overlaying a proton with KE < 225 MeV onto 25% of our background events with a target neutron